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Inoue et al.

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(54) **POWER CONVERSION APPARATUS AND ELECTRICAL-MECHANICAL ENERGY CONVERSION SYSTEM**

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(22) Filed: **Jul. 1, 2014**

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(30) **Foreign Application Priority Data**

Jul. 2, 2013 (JP) 2013-138804

(51) **Int. Cl.**

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H02P 6/14	(2016.01)
H02M 7/483	(2007.01)
H02P 25/16	(2006.01)

(52) **U.S. Cl.**

CPC ***H02P 6/14*** (2013.01); ***H02M 7/483*** (2013.01); *H02M 2007/4835* (2013.01); *H02P 25/16* (2013.01); *H02P 27/04* (2013.01)

(58) **Field of Classification Search**

USPC 318/800, 801, 139; 363/34, 35, 36, 37, 363/40, 67, 71, 87, 95, 98, 120, 124, 175, 363/176

See application file for complete search history.

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(57) **ABSTRACT**

A power conversion apparatus includes arms in each of which one or more unit converters each including a capacitor and capable of outputting an arbitrary voltage are connected in series, and a point P as a first node to which one end of the respective arms are Y-connected, and a point N as a second node to which a neutral terminal of the rotary electric machine is connected. The other end of the respective arms are connected to one ends of respective phase windings of a rotary electric machine.

11 Claims, 7 Drawing Sheets

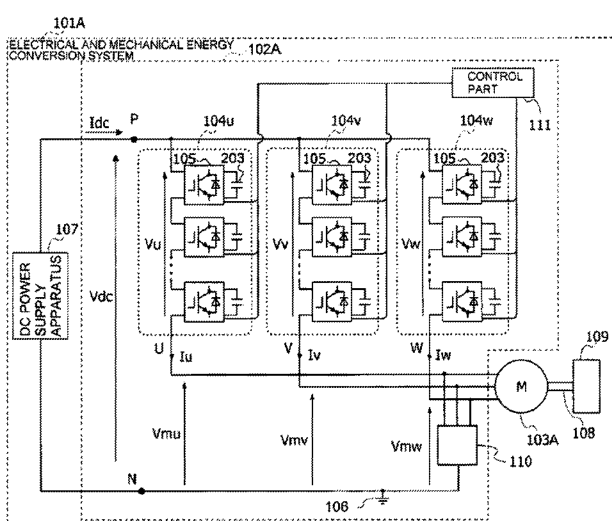
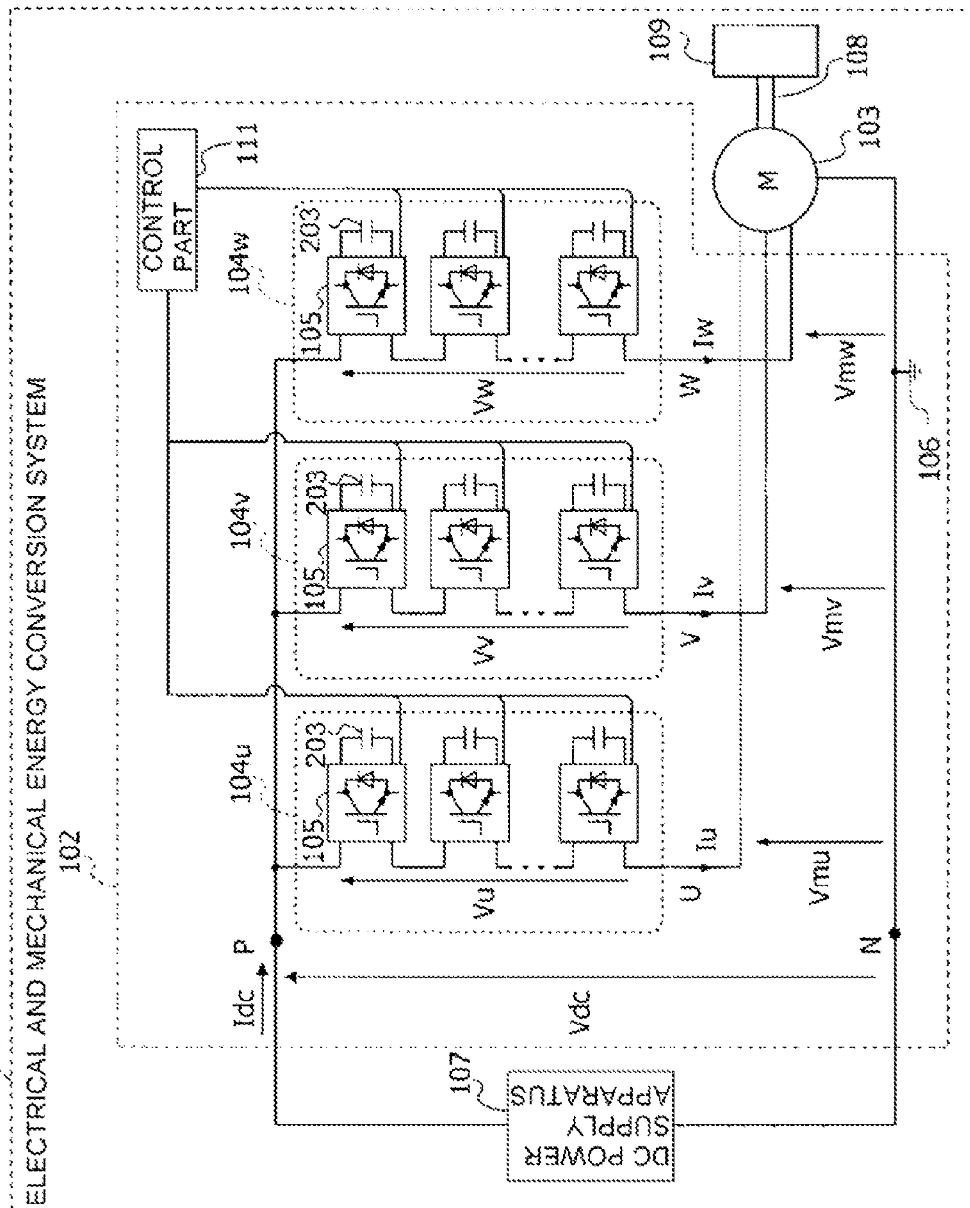


FIG. 1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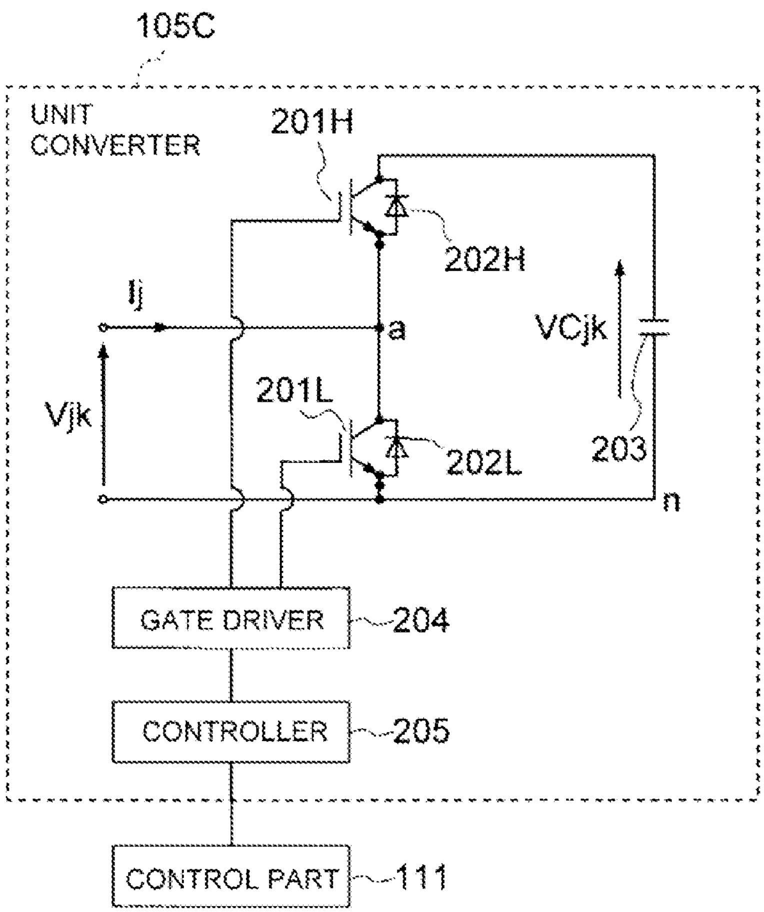
ELECTRICAL AND MECHANICAL ENERGY CONVERSION SYSTEM
102
CONTROL PART
111
104u
104v
104w
105
203
P
N
Idc
Vdc
U
V
W
Iu
Iv
Iw
Vu
Vv
Vw
Vmu
Vmv
Vmw
106
M
103
108
109
107
DC POWER SUPPLY APPARATUS

FIG. 2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UNIT CONVERTER
201H
202H
Ij
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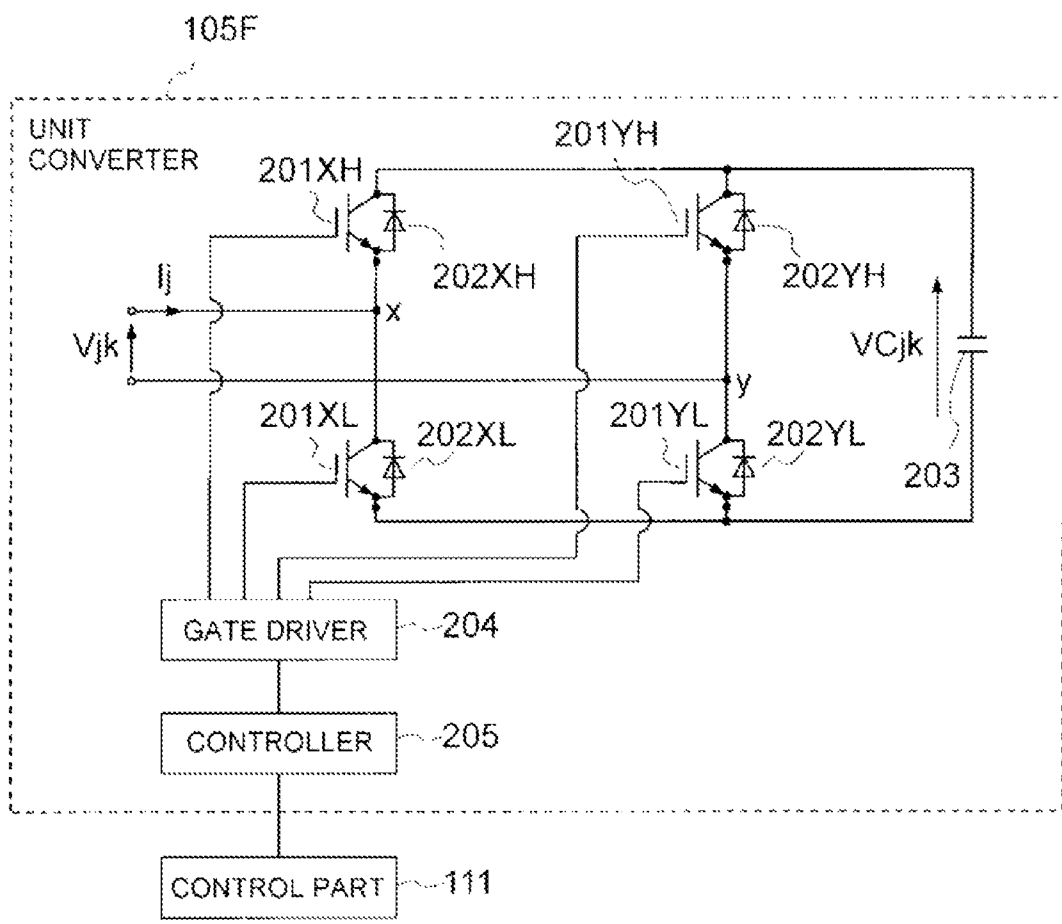
VCjk
Vjk
201L
202L
203
n
GATE DRIVER
204
CONTROLLER
205
CONTROL PART
111

FIG. 3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x
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VCjk
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202YL
203
GATE DRIVER
204
CONTROLLER
205
CONTROL PART
111

FIG. 4A

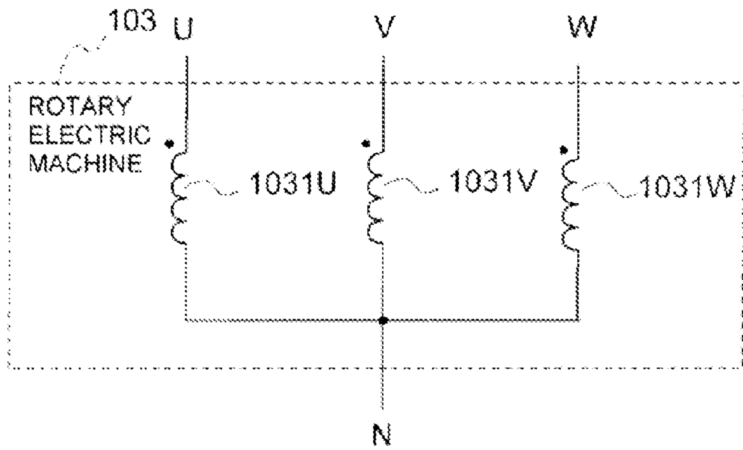


FIG. 4B

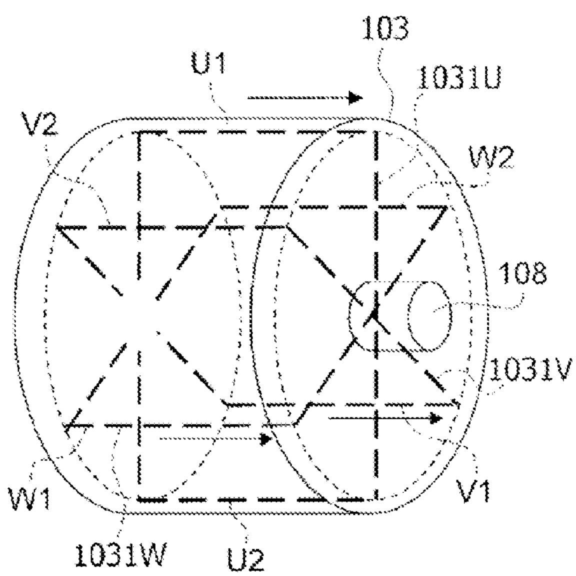


FIG. 4C

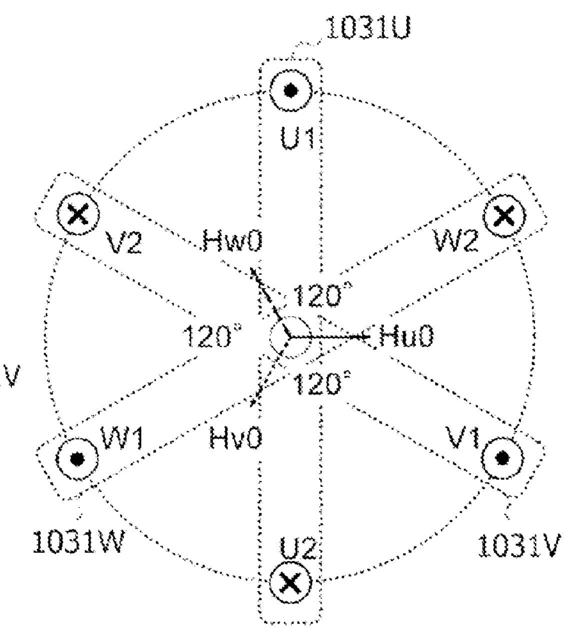


FIG. 5

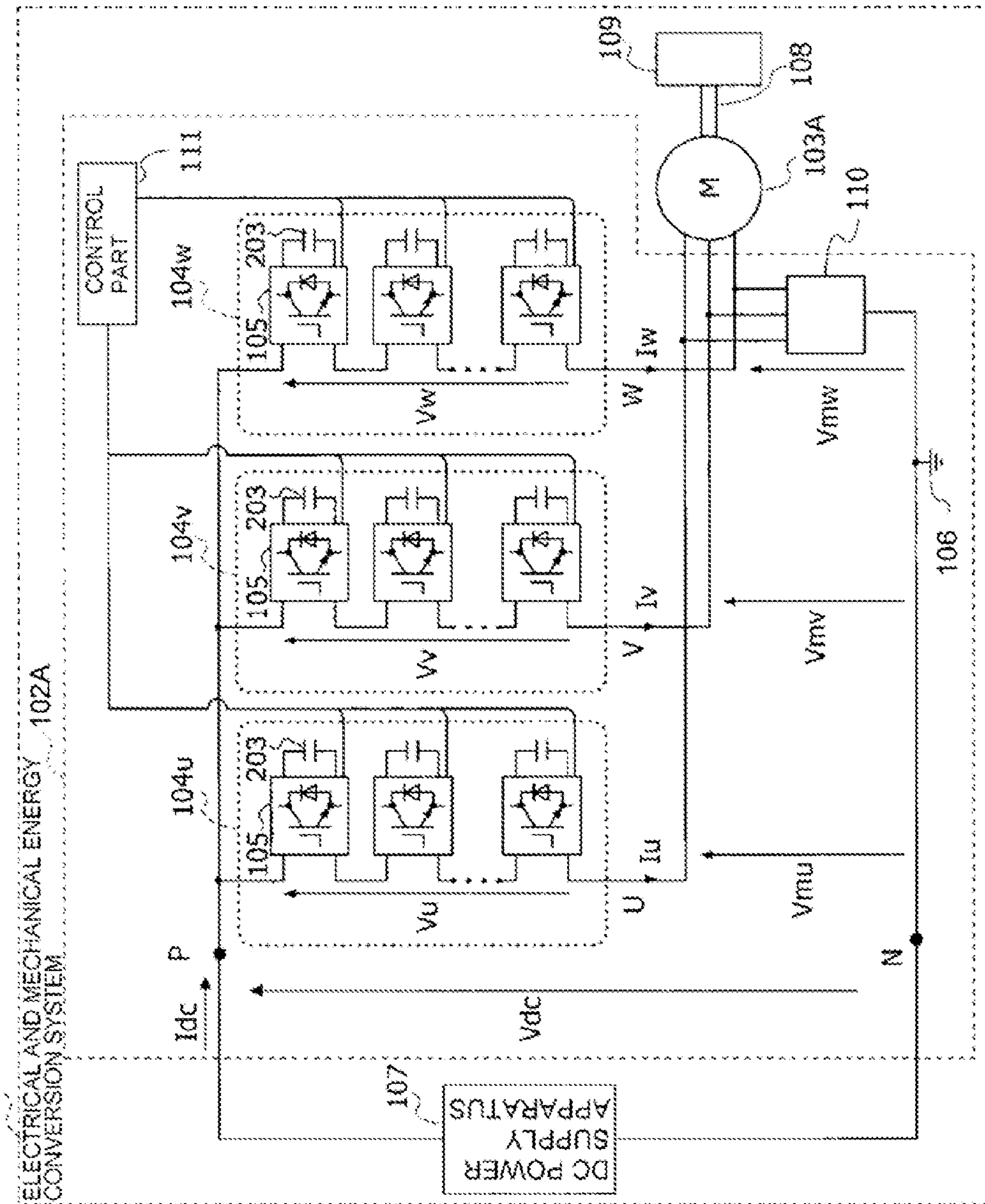
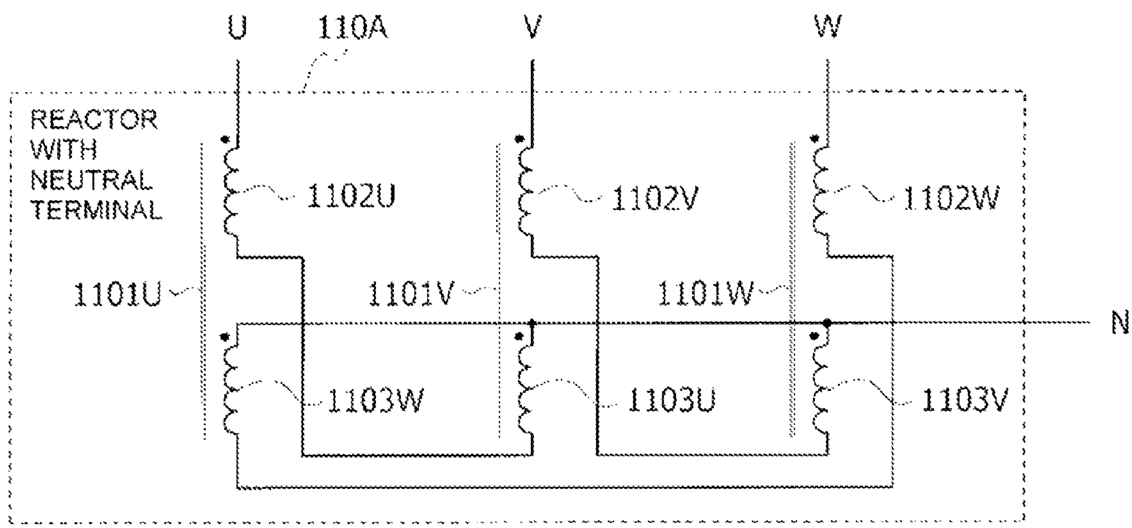

101A
ELECTRICAL AND MECHANICAL ENERGY CONVERSION SYSTEM
102A
CONTROL PART
111
104u
104v
104w
105
203
P
N
Idc
Vdc
U
V
W
Iu
Iv
Iw
Vu
Vv
Vw
Vmu
Vmv
Vmw
106
107
DC POWER SUPPLY APPARATUS
103A
M
108
109
110

FIG. 6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V
W
REACTOR
WITH
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1102V
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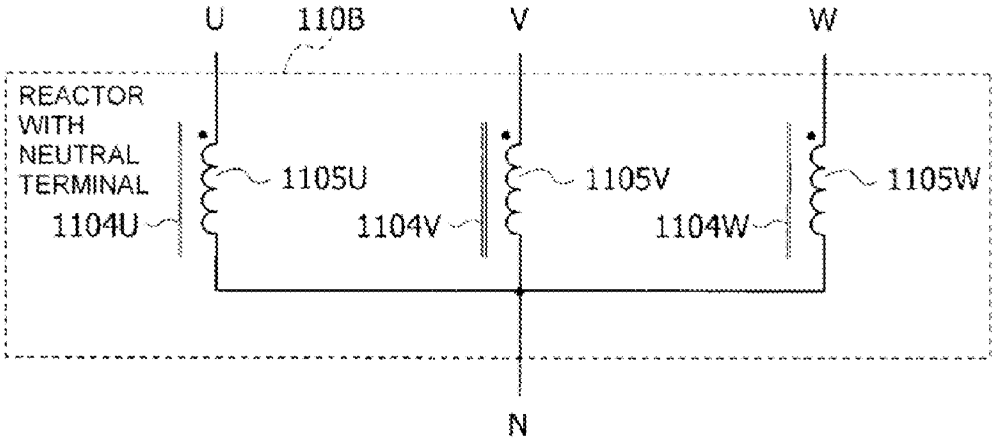
N
1103W
1103U
1103V

FIG. 7A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V
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WITH
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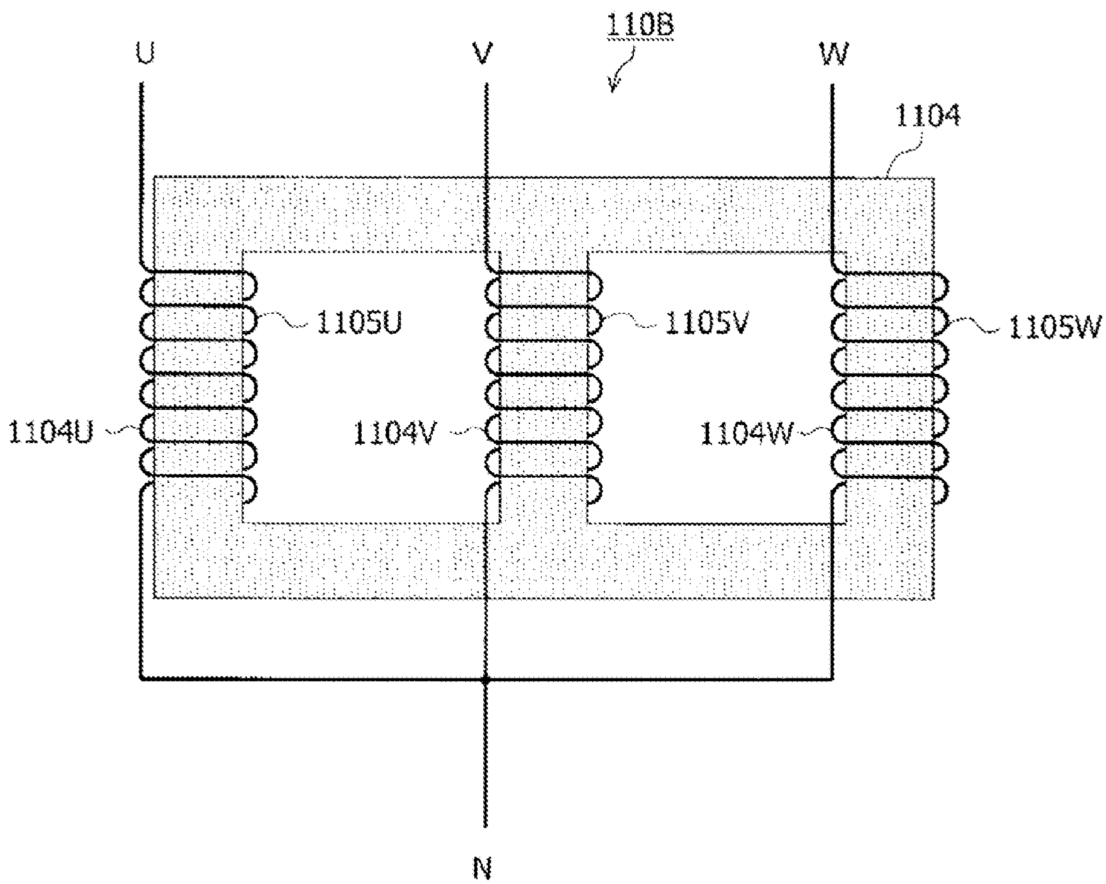
TERMINAL
1105U
1105V
1105W
1104U
1104V
1104W
N

FIG. 7B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U
V
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1105W
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1104V
1104W
N

POWER CONVERSION APPARATUS AND ELECTRICAL-MECHANICAL ENERGY CONVERSION SYSTEM

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a power conversion apparatus for converting DC power into AC power or AC power to DC power, and an electrical-mechanical energy conversion system using this power conversion apparatus.

2. Description of Related Art

The preface of Non Patent Literature 1 (Makoto Hagiwara, Kazutoshi Nishimura, Hirofumi Akagi, "A Medium-Voltage Motor Drive with a Modular Multilevel PWM Inverter Part I. Experimental Verification by a400-V, 15-kW Downscaled Model", IEEJ Transactionson Industry Applications, April 2010, Vol. 130, No. 4, pp. 544-551) states that "In this paper, the feasibility of a medium-voltage motor drive using a three-phase MMI is considered. A downscaled model of 400V, 15 kW is designed and built, and the control method and operation characteristics will be verified." FIG. 1(a) of Non Patent Literature 1 shows a main circuit structure of the three-phase MMI. The MMI is an abbreviation of Modular Multi-level PWM (Pulse Width Modulation) Inverter. The three-phase MMI is a power conversion apparatus in which series circuits each including an arm of a series circuit of one or more unit converters and a reactor are connected in three phase bridge configuration. FIGS. 3 to 5 of Non Patent Literature 1 show experimental results obtained by driving an AC motor connected to the AC output terminal of the three-phase MMI.

The three-phase MMI is a kind of multi-level converter and uses a switching element capable of controlling ON/OFF, such as an IGBT (Insulated-Gate Bipolar Transistor), a GTO (Gate Turn-Off Thyristor) or a GCT (Gate-Commutated Thyristor) and can output a voltage higher than the withstand voltage of the switching element.

The power conversion apparatus shown in FIG. **1** (*a*) of Non Patent Literature 1 requires one reactor for each phase in order to suppress a current circulating through each arm. Thus, the volume and weight of the whole power conversion apparatus may be large, and the installation footprint also may be large.

Further, since the reactor is provided between the arm of each phase and the rotary electric machine, the arm voltage can not be directly applied to the rotary electric machine, and there is the likelihood that the controllability of the rotary electric machine is reduced.

SUMMARY OF THE INVENTION

The invention provides a power conversion apparatus in which a rotary electric machine and an arm can be connected to each other without a reactor, and an electrical-mechanical energy conversion system using this power conversion apparatus.

According to a first aspect of the invention, a power conversion apparatus includes three or more arms in each of which one or more unit converters each including an energy storage element and capable of outputting an arbitrary voltage are connected in series, and a first node to which one ends of the respective arms are Y-connected, and other ends of the respective arms are connected to one ends of respective phase windings of a rotary electric machine.

By this, since the arms and the respective phase windings of the rotary electric machine are connected to each other without a reactor, the controllability of the rotary electric machine can be improved. Besides, since a reactor for each phase is not required, the volume and weight of the whole power conversion apparatus is made compact and the power conversion apparatus can be installed in a small area.

According to a second aspect of the invention, an electrical-mechanical energy conversion system includes a power conversion apparatus which includes three or more arms in each of which one or more unit converters each including an energy storage element and capable of outputting an arbitrary voltage are connected in series, and a first node to which one end of the respective arms are Y-connected, and a rotary electric machine to which a mechanical load is connected and in which other end of the respective arms are connected to one end of respective phase windings.

By this, the controllability of the rotary electric machine is improved, the volume and weight of the whole power conversion apparatus is made compact, and the power conversion apparatus can be installed in a small area. Accordingly, the compact and well-controllable electrical-mechanical energy conversion system can be provided.

Other aspects of the invention will be described in the column of Description of Embodiments.

According to the aspects of the invention, the power conversion apparatus in which the rotary electric machine and the arm can be connected to each other without a reactor, and the electrical-mechanical energy conversion system using the power conversion apparatus can be provided.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic structural view showing a power conversion apparatus of a first embodiment.

FIG. **2** is a view showing a unit converter of a bi-directional chopper circuit system.

FIG. **3** is a view showing a unit converter of a full-bridge circuit system.

FIGS. **4**A to **4**C are views showing a structure and an operation of a rotary electric machine in the first embodiment.

FIG. **5** is a schematic structural view showing a power conversion apparatus of a second embodiment.

FIG. **6** is a view showing a reactor with a neutral terminal in the second embodiment.

FIGS. **7**A and **7**B are views showing a reactor with a neutral terminal in a modified example of the second embodiment.

DESCRIPTION OF EMBODIMENTS

Hereinafter, embodiments of the invention will be described with reference to the drawings.

First Embodiment

FIG. **1** is a schematic structural view showing a power conversion apparatus **102** of a first embodiment.

As shown in FIG. **1**, an electrical-mechanical energy conversion system **101** includes a DC power supply apparatus **107**, the power conversion apparatus **102**, a rotary electric machine **103** and a mechanical load **109**.

The DC power supply apparatus **107** supplies DC power through the point P and the point N. The DC power supply apparatus **107** is, for example, a diode rectifier, a thyristor rectifier, a PWM rectifier, a modular multi-level rectifier, a battery, a secondary battery or a DC power system, and is arbitrary as long as the DC power can be supplied.

The power conversion apparatus **102** converts the DC power supplied from the DC power supply apparatus **107** through the point P and the point N into AC power, and drives the rotary electric machine **103** connected to the point U, the point V and the point W. The rotary electric machine **103** is, for example, a three-phase motor. The point U is one end of the U-phase winding of the rotary electric machine **103**. The point V is one end of the V-phase winding of the rotary electric machine **103**. The point W is one end of the W-phase winding of the rotary electric machine **103**. The respective phase windings of the rotary electric machine **103** are Y-connected and are connected to the point N as a second node.

The rotary electric machine **103** is mechanically connected to a shaft **108** and the mechanical load **109**. The mechanical load **109** is connected to the shaft **108** and is rotated and driven. By this, the electrical-mechanical energy conversion system **101** can convert the electrical energy supplied as the DC power into mechanical energy.

The point U, the point V and the point W are one ends of stator windings of the rotary electric machine **103**. Incidentally, the point U, the point V and the point W may be one ends of rotor windings of the rotary electric machine **103**, and a neutral terminal to which the other ends of the rotor windings are Y-connected may be connected to the point N as the second node. In the following description, the description will be made without particularly distinguishing whether the point U, the point V and the point W are one ends of the stator windings or one ends of the rotor windings.

Next, an inner structure of the power conversion apparatus **102** will be described.

The power conversion apparatus **102** includes three arms **104***u*, **104***v* and **104***w*, and a control part **111**. Each of the arms **104***u*, **104***v* and **104***w* is constructed such that one or more unit converters **105** each including a capacitor **203** as an energy storage element and capable of outputting an arbitrary voltage are connected in series. Hereinafter, when the arms **104***u*, **104***v* and **104***w* are not particularly distinguished, they are respectively simply referred to as an arm **104**. In the first embodiment, since the number of phases of the rotary electric machine **103** is three, the number of the arms **104** is three. However, no limitation is made to this. If the number of phases of the rotary electric machine **103** is four or more, the same number of arms **104** as the number of phases may be provided, and three or more arms may be provided.

One ends of the arms **104***u*, **104***v* and **104***w* are Y-connected to the point P as a first node. The other end of the arm **104***u* is connected to one end of the U-phase winding of the rotary electric machine **103** through the point U. The other end of the arm **104***v* is connected to one end of the V-phase winding of the rotary electric machine **103** through the point V. The other end of the arm **104***w* is connected to one end of the W-phase winding of the rotary electric machine **103** through the point W.

The neutral terminal of the rotary electric machine **103** is a node to which the other end of the U-phase winding, the other end of the V-phase winding and the other end of the W-phase winding are connected, and is connected to the point N as the second node. By this, the power conversion apparatus **102** supplies AC current to the respective phase windings of the rotary electric machine **103** and can rotate and drive.

The point N as the second node is further connected to a ground point **106**. Thus, the neutral terminal of the rotary electric machine **103** is grounded through the second node. Accordingly, the DC component of ground potential of the rotary electric machine **103** can be made substantially zero and there is no fear of electric leakage.

The DC power supply apparatus **107** is connected to the point P and the point N.

The control part **111** controls one or plural unit converters **105** constituting each of the arms **104***u*, **104***v* and **104***w*. The control part **111** is connected to the respective unit converters **105** constituting each of the arms **104***u*, **104***v* and **104***w*, and controls the output voltage, and accordingly controls the rotation driving of the rotary electric machine **103**.

Here, for convenience of description, voltages and currents shown in FIG. **1** are defined as follows.

A voltage between the point P and the point N is a DC voltage Vdc. A current flowing from the DC power supply apparatus **107** to the point P is a DC current Idc.

The arm **104***u* outputs an arm voltage Vu. The arm **104***v* outputs an arm voltage Vv. The arm **104***w* outputs an arm voltage Vw. Incidentally, each of the arm voltages Vu, Vv and Vw is the sum of output voltages of the respective unit converters **105** included in each of the arms **104***u*, **104***v* and **104***w*. An arm current Iu flows from the arm **104***u* to the point U. An arm current Iv flows from the arm **10***v* to the point V. An arm current Iw flows from the arm **104***w* to the point W.

An applied voltage Vmu is a voltage applied between the point U of the rotary electric machine **103** and the point N.

An applied voltage Vmv is a voltage applied between the point V of the rotary electric machine **103** and the point N. An applied voltage Vmw is a voltage applied between the point W of the rotary electric machine **103** and the point N.

Hereinafter, an example of an inner structure of the unit converter **105** and a control method of output voltage will be described by use of FIG. **2** and FIG. **3**.

In the power conversion apparatus **102**, for example, a unit converter **105**C (see FIG. **2**) of a bi-directional chopper circuit system capable of outputting a monopolar voltage can be used as the unit converter **105**. By this, in the power conversion apparatus **102**, the number of switching elements intervening between the input/output terminal of the unit converter **105**C and the capacitor **203** as the energy storage element can be made one as the minimum number. Accordingly, energy loss due to power conversion can be reduced.

Further, in the power conversion apparatus **102**, a unit converter **105**F (see FIG. **3**) of a full-bridge circuit system capable of outputting a bipolar voltage can be used as the unit converter **105**. By this, the power conversion apparatus **102** can output a positive voltage and a negative voltage of the capacitor **203** as the energy storage element and a zero voltage from the input/output terminal of the unit converter **105**F. Thus, even when AC power is supplied to the power conversion apparatus **102**, the rotary electric machine **103** can be rotated and driven.

Each of the arms **104** of the first embodiment is constructed of only the unit converter **105**C (see FIG. **2**) of the bi-directional chopper circuit system. However, no limitation is made to this, and each of the arms **104** may be constructed of only the unit converter **105**F (see FIG. **3**) of the full-bridge circuit system. Further, each of the arms **104** may be constructed such that the unit converter **105**C (see FIG. **2**) of the bi-directional chopper circuit system and the unit converter **105**F (see FIG. **2**) of the full-bridge circuit system are mixed. By this, the effect of reduction in energy loss due to power conversion and the effect of increase in the degree of freedom of input and output voltages by the bipolar voltage output can be obtained.

FIG. **2** is a view showing the unit converter **105**C of the bi-directional chopper circuit system.

As shown in FIG. **2**, the unit converter **105**C includes a circuit in which an upper switching element **201**H and a free-wheeling diode **202**H are reversely parallel-connected, a circuit in which a lower switching element **201**L and a free-wheeling diode **202**L are reversely parallel-connected, and a capacitor **203**.

A cathode of the free-wheeling diode **202**H is connected to a collector of the upper switching element **201**H and is connected to one end of the capacitor **203**. An emitter of the switching element **201**H is connected to an anode of the free-wheeling diode **202**H and is connected to one input/output terminal of the unit converter **105** through a point "a". Agate driver **204** is connected to agate of the switching element **201**H.

Similarly, a collector of the lower switching element **201**L is connected to a cathode of the free-wheeling diode **202**L and is connected to the point "a". An emitter of the switching element **201**L is connected to an anode of the free-wheeling diode **202**L and is connected to the other input/output terminal of the unit converter **105**C, and is further connected to the other end of the capacitor **203** through a point "n". The gate driver **204** is connected to a gate of the switching element **201**L. The gate driver **204** is electrically connected to a controller **205**. The controller **205** is connected to the control part **111** through an optical fiber.

The capacitor **203** is, for example, an electrolytic capacitor, and is the energy storage element of the unit converter **105**C of the bi-directional chopper circuit system.

In the specification, the upper switching element **201**H and the lower switching element **201**L, and an after-mentioned X-phase upper switching element **201**XH, an X-phase lower switching element **201**XL, a Y-phase upper switching element **201**YH, and a Y-phase lower switching element **201**YL shown in FIG. **3** are sometimes collectively called as a switching element **201**.

As shown in FIG. **2**, in the first embodiment, an IGBT is used as the switching element **201**. However, no limitation is made to this. In the invention, another kind of a switching element which is a power semiconductor device capable of controlling ON and OFF, such as a GTO, a GCT or a MOSFET (Metal-Oxide-Semiconductor Field Effect Transistor), may be used as the switching element **201**.

An output voltage Vjk is a voltage applied between the point "a" of FIG. **2** and the point "n" as the other end of the capacitor **203**, and is the output voltage of the unit converter **105**C of the bi-directional chopper circuit system. Here, j denotes one of a u phase, a v phase and a w phase. Besides, k denotes a natural number between 1 and M, and M denotes the number of the unit converters **105**C included in each of the arms **104***u*, **104***v* and **104***w*.

A current Ij flows from the one input/output terminal of the unit converter **105**C to the point "a". Here, j is a symbol indicating one of the u phase, the v phase and the w phase.

Hereinafter, a relation between the output voltage Vjk and the on/off states of the switching elements **201**H and **201**L will be described.

When the upper switching element **201**H is on and the lower switching element **201**L is off, control can be made so that the output voltage Vjk becomes substantially equal to a capacitor voltage VCjk irrespective of the current Ij.

When the upper switching element **201**H is off and the lower switching element **201**L is on, control can be made so that the output voltage Vjk becomes substantially equal to zero irrespective of the current Ij.

FIG. **3** is a view showing the unit converter **105**F of the full-bridge circuit system.

As shown in FIG. **3**, the unit converter **105**F includes an X-phase circuit in which a circuit including the upper switching element **201**XH and a free-wheeling diode **202**XH inversely parallel connected to each other is connected in series to a circuit including the lower switching element **201**XL and a free-wheeling diode **202**XL inversely parallel connected to each other.

Besides, the unit converter **105**F includes a Y-phase circuit in which a circuit, including the upper switching element **201**YH and a free-wheeling diode **202**YH which are inversely parallel connected to each other, is connected in series to a circuit including the lower switching element **201**YL and a free-wheeling diode **202**YL inversely parallel connected to each other, and further, a capacitor **203** is parallel connected to the X-phase circuit and the Y-phase circuit.

In the X-phase circuit, a collector of the upper switching element **201**XH is connected to a cathode of the free-wheeling diode **202**XH and is connected to one end of the capacitor **203**. An emitter of the switching element **201**XH is connected to an anode of the free-wheeling diode **202**XH and is connected to one input/output terminal of the unit converter **105**F through a point "x". A gate of the switching element **201**XH is connected to a gate driver **204**.

Similarly, a collector of the lower switching element **201**XL is connected to a cathode of the free-wheeling diode **202**XL and is connected to the point "x". An emitter of the switching element **201**XL is connected to an anode of the free-wheeling diode **202**XL and is connected to the other end of the capacitor **203**. A gate of the switching element **201**XL is connected to the gate driver **204**.

In the Y-phase circuit, a collector of the upper switching element **201**YH is connected to a cathode of the free-wheeling diode **202**YH and is connected to the one end of the capacitor **203**. An emitter of the switching element **201**YH is connected to an anode of the free-wheeling diode **202**YH and is connected to the other input/output terminal of the unit converter **105**F through a point "y". A gate of the switching element **201**YH is connected to the gate driver **204**.

Similarly, a collector of the lower switching element **201**YL is connected to a cathode of the free-wheeling diode **202**YL and is connected to the point "y". An emitter of the switching element **201**YL is connected to an anode of the free-wheeling diode **202**YL and is connected to the other end of the capacitor **203**. A gate of the switching element **201**YL is connected to the gate driver **204**.

The gate driver **204** is electrically connected to a controller **205**. The controller **205** is connected to a control part **111** through an optical fiber.

The capacitor **203** is the energy storage element of the unit converter **105**F. Incidentally, no limitation is made to this. In the unit converter **105**F, instead of the capacitor **203**, a secondary battery or the like may be used as the energy storage element.

An output voltage Vjk is a voltage applied between the point "x" and the point "y", and is the output voltage of the unit converter **105**F of the full-bridge circuit system. A current Ij flows from one input/output terminal of the unit converter **105**F to the point x.

Hereinafter, a relation between the output voltage Vjk and the on/off states of the switching elements **201**XH, **201**XL, **201**YH and **201**YL.

When the X-phase upper switching element **201**XH is on, the lower switching element **201**XL is off, the Y-phase upper switching element **201**YH is on, and the lower switching element **201**YL is off, control can be made so that the output voltage Vjk becomes substantially equal to zero irrespective of the current Ij.

When the X-phase upper switching element **201**XH is on, the lower switching element **201**XL is off, the Y-phase upper switching element **201**YH is off, and the lower switching element **201**YL is on, control can be made so that the output voltage Vjk becomes substantially equal to a capacitor voltage VCjk irrespective of the current Ij.

When the X-phase upper switching element **201**XH is off, the lower switching element **201**XL is on, the Y-phase upper switching element **201**YH is on, and the lower switching element **201**YL is off, control can be made so that the output voltage Vjk becomes substantially equal to a voltage (−VCjk) of a polarity reverse to the polarity of the capacitor voltage VCjk irrespective of the current Ij.

When the X-phase upper switching element **201**XH is off, the lower switching element **201**XL is on, the Y-phase upper switching element **201**YH is off, and the lower switching element **201**YL is on, control can be made so that the output voltage Vjk becomes substantially equal to zero irrespective of the current Ij.

Hereinafter, a method of controlling the applied voltages Vmu, Vmv and Vmw to the rotary electric machine **103** and a method of controlling the operation of the rotary electric machine **103** through the applied voltages Vmu, Vmv and Vmx will be described.

First, each of the arm voltages Vu, Vv and Vw outputted by the respective arms **104***u*, **104***v* and **104***w* is the sum of the output voltage Vjk of the one or plural unit converters **105** included in the arm **104**. Thus, if the output voltage of each of the unit converters **105** is controlled, the arm voltages Vu, Vv and Vw can be controlled.

The applied voltages Vmu, Vmv and Vmw to the rotary electric machine **103**, the DC voltage Vdc, and the arm voltages Vu, Vv and Vw satisfy expressions (1) to (3).

The U-phase applied voltage Vmu to the rotary electric machine **103** is obtained by subtracting the arm voltage Vu from the DC voltage Vdc as indicated by expression (1).

$$Vmu=Vdc-Vu \tag{1}$$

The V-phase applied voltage Vmv to the rotary electric machine **103** is obtained by subtracting the arm voltage Vv from the DC voltage Vdc as indicated by expression (2).

$$Vmv=Vdc-Vv \tag{2}$$

The W-phase applied voltage Vmw of the rotary electric machine **103** is obtained by subtracting the arm voltage Vw from the DC voltage Vdc as indicated by expression (3).

$$Vmw=Vdc-Vw \tag{3}$$

In other words, the respective arms **104***u*, **104***v* and **104***w* can apply arbitrary voltages to the respective phases of the rotary electric machine **103** based on the expressions (1) to (3) by controlling the arm voltages Vu, Vv and Vw. If the control part **111** controls so that the DC voltage Vdc becomes substantially equal to the DC components included in the arm voltages Vu, Vv and Vw, control can be made so that the applied voltages Vmu, Vmv and Vmw to the rotary electric machine **103** include only AC components. From the above, the control part **111** can control so that the applied voltages Vmu, Vmv and Vmw to the rotary electric machine **103** become three-phase AC voltages of adjustable amplitude and adjustable frequency.

The control part **111** can control the applied voltages Vmu, Vmv and Vmw to the rotary electric machine **103** to the adjustable-amplitude and adjustable-frequency three-phase AC voltage. Thus, the torque, rotation speed, position and the like of the rotary electric machine **103** can be controlled by performing, for example, V/f control or vector control.

Incidentally, according to the invention, if the amplitudes of the applied voltages Vmu, Vmv and Vmw to the rotary electric machine are made the same, as compared with the comparative example disclosed in Non Patent Literature 1, there is also an effect that the DC voltage Vdc can be reduced to ½. The reason will be described below.

In the comparative example disclosed in Non Patent Literature 1, eight unit converters are used for each phase, the eight unit converters are divided into four positive side converters and four negative side converters, and the four unit converters respectively share ¼ of AC voltage. With respect to DC voltage, the eight unit converters respectively share ⅛. In other words, if the number of unit converters provided for each phase is M, (M/2) unit converts share AC voltage, and M unit converters share DC voltage.

In this embodiment, M unit converters **105** share both AC voltage and DC voltage. Thus, if AC voltage of the same amplitude is outputted, DC voltage can be reduced to ½ as compared with the comparative example.

As shown in FIG. **1**, the arm currents Iu, Iv and Iw include positive-sequence and zero-sequence components. The positive-sequence components of the arm currents Iu, Iv and Iw form rotating magnetic field in the rotary electric machine **103**, and contribute to the control of the torque, rotation speed, position and the like of the rotary electric machine **103**. The zero-sequence components of the arm currents Iu, Iv and Iw correspond to ⅓ of the sum of the respective arm currents Iu, Iv and Iw. The sum of the respective arm currents Iu, Iv and Iw is equal to the DC current Idc. By this, the zero-sequence components of the arm currents Iu, Iv and Iw correspond to ⅓ of the DC current Idc. Accordingly, Idc/3 flows as the zero-sequence currents through the rotary electric machine **103**. The magnetic field of the rotary electric machine **103** generated by the zero-sequence currents becomes zero. Thus, the zero-sequence currents do not influence the control of the torque, rotation speed, position and the like of the rotary electric machine **103**.

Hereinafter, with reference to FIGS. **4**A to **4**C, a description will be made on a fact that when ⅓ (=Idc/3) of the DC current Idc flows as the zero-sequence current through the rotary electric machine **103**, the magnetic field of the rotary electric machine **103** becomes substantially zero.

FIGS. **4**A to **4**C are views showing the structure and operation of the rotary electric machine **103**. FIG. **4**A is a circuit view of the inside of the rotary electric machine **103**. FIG. **4**B is a perspective view of the rotary electric machine **103**. FIG. **4**C is a view showing magnetic fields of the rotary electric machine **103** by zero-sequence currents.

As shown in FIG. **4**A, the rotary electric machine **103** includes a U-phase winding **1031**U, a V-phase winding **1031**V and a W-phase winding **1031**W, and these are Y-connected and are connected to a neutral terminal N.

As shown in FIG. **4**B, in the rotary electric machine **103**, the U-phase winding **1031**U, the V-phase winding **1031**V and the W-phase winding **1031**W are wound at positions mechanically different from each other by 120 degrees. By this, the positive-sequences components of the arm currents Iu, Iv and Iw can form rotating magnetic fields.

FIG. **4**C is a sectional view perpendicular to the rotation shaft of the rotary electric machine **103** shown in FIG. **4**B, and shows the respective windings **1031**U, **1031**V and **1031**W. In FIG. **4**C, positive-sequence components included in the arm currents Iu, Iv and Iw are neglected, and only magnetic fields Hu0, Hv0 and Hw0 generated by the zero-sequence components (Idc/3) are shown.

The zero-sequence component (Idc/3) of the arm current Iu flowing through the U-phase arm **104***u* and the U-phase winding **1031**U of the rotary electric machine **103** flows in a direction from back to front of the drawing at a point U1, and flows in a direction from front to back of the drawing at a point

U2. The zero-sequence (Idc/3) of the arm current Iu flowing through the U-phase winding **1031**U forms a magnetic field Hu0.

The zero-sequence component (Idc/3) of the arm current Iv flowing through the V-phase arm **104***v* and the V-phase winding **1031**V of the rotary electric machine **103** flows in the direction from back to front of the drawing at a point V1, and flows in the direction from front to back of the drawing at a point V2. The zero-sequence (Idc/3) of the arm current Iv flowing through V-phase winding **1031**V forms a magnetic field Hv0.

The zero-sequence component (Idc/3) of the arm current Iw flowing through the W-phase arm **104***w* and the W-phase winding **1031**W of the rotary electric machine **103** flows in the direction from back to front of the drawing at a point W1, and flows in the direction from front to back of the drawing at a point W2. The zero-sequence (Idc/3) of the arm current Iw flowing through the W-phase winding **1031**W forms a magnetic field Hw0.

As shown in FIG. **4**C, the magnetic fields Hu0, Hv0 and Hw0 formed by the zero-sequence currents Idc/3 flowing through the three windings **1031**U, **1031**V and **1031**W have vectors having the same magnitude and directions different from each other by 120 degrees. Thus, the vector sum of the magnetic fields Hu0, Hv0 and Hw0 becomes zero. In other words, the zero-sequence currents Idc/3 flowing through the respective windings **1031**U, **1031**V and **1031**W do not form magnetic field in the rotary electric machine **103**. Accordingly, the zero-sequence currents Idc/3 do not influence the control of the torque, rotation speed, position and the like.

In the above, it has been described that the torque, rotation speed, position and the like of the rotary electric machine **103** can be controlled through the arm voltages Vu, Vv and Vw, and even if ⅓ of the DC current Idc flows through the rotary electric machine **103**, the control of the torque, rotation speed, position and the like is not influenced.

According to the first embodiment, there is an effect that the power conversion apparatus **102** for driving the rotary electric machine **103** can be constructed without using one reactor for each phase, which is inevitable in the comparative example (Non Patent Literature 1).

Further, when the mechanical load **109** is mechanically connected to the shaft **108** of the rotary electric machine **103** of the power conversion apparatus **102**, there is an effect that an electrical-mechanical energy conversion system including the mechanical load **109** of the rotary electric machine **103** can be constructed.

In the comparative example (Non Patent Literature 1), when one end of a DC terminal is grounded, the DC component of ground potential of the rotary electric machine becomes ½ of the DC voltage outputted by the DC power supply apparatus. On the other hand, in the power conversion apparatus **102** of the first embodiment, the DC component of ground potential of the rotary electric machine **103** can be made substantially zero. Thus, there are effects that the thickness of an insulation material for securing dielectric strength of the rotary electric machine **103** can be reduced, and a space between the rotary electric machine **103** and the outside can be narrowed.

Second Embodiment

FIG. **5** is a schematic structural view showing a power conversion apparatus **102**A of a second embodiment. The same components as those of the power conversion apparatus **102** of the first embodiment shown in FIG. **1** are denoted by the same reference numerals.

An electrical-mechanical energy conversion system **101**A of the second embodiment shown in FIG. **5** includes the power conversion apparatus **102**A different from the first embodiment and a rotary electric machine **103**A. The power conversion apparatus **102**A of the second embodiment includes a reactor **110** with a neutral terminal in addition to the same structure as that of the first embodiment.

In the power conversion apparatus **102**A of the second embodiment, one ends of respective arms **104** in each of which one or more unit converters **105** are connected in series are Y-connected to a point P as a first node, and the other ends of the respective arms **104** are connected in parallel to one ends of respective phase windings of the rotary electric machine **103**A and one ends of respective phase windings of the reactor **110** with the neutral terminal. The neutral terminal of the reactor **110** with the neutral terminal is connected to a point N as a second node. A DC power supply apparatus **107** supplies DC power to the power conversion apparatus **102**A through the point P and the point N.

In the rotary electric machine **103**A, the neutral terminal is not drawn differently from the rotary electric machine **103** (see FIG. **1**) of the first embodiment. According to the second embodiment, the same effect as the first embodiment can be obtained, and further, there is an effect that the power conversion apparatus **102**A for driving the rotary electric machine **103**A can be constructed without using the neutral terminal of the rotary electric machine **103**A differently from the first embodiment. By this, the invention can be applied not only to the Y-connected rotary electric machine **103**A but also to the Δ-connected rotary electric machine.

The neutral terminal of the reactor **110** with the neutral terminal is connected to a ground point **106** through the point N. By doing so, similarly to the first embodiment, the DC component of the ground potential of the rotary electric machine **103**A can be made substantially zero, and the ground potential of the reactor **110** with the neutral terminal can be reduced. Thus, there is no fear of electric leakage.

A DC current Idc branches into three currents, flows through respective arms **104***u*, **104***v* and **104***w*, and flows to the point N as the second node through the reactor **110** with the neutral terminal. Incidentally, a reactor as in the comparative example is not connected to a current path from each of the arms **104***u*, **104***v* and **104***w* to the rotary electric machine **103**A.

In the comparative example disclosed in Non Patent Literature 1, in order to suppress circulation current flowing between arms, a reactor is connected between an upper arm and a lower arm of each phase. On the other hand, in the power conversion apparatus **102**A of the second embodiment, since the reactor **110** with the neutral terminal suppresses the circulation current, it is unnecessary to connect a reactor between the rotary electric machine **103**A and each of the arms **104***u*, **104***v* and **104***w*. Thus, arm voltages Vu, Vv and Vw outputted by the arms **104***u*, **104***v* and **104***w* can be directly applied to the rotary electric machine **103**A without a reactor. By this, there is obtained an effect that the controllability of the rotary electric machine **103**A can be improved.

Three-phase AC power does not pass through the reactor **110** with the neutral terminal, but only DC power passes. Thus, it is preferable that in the reactor **110** with the neutral terminal, positive-sequence inductance is designed to be large, and zero-sequence inductance is made small. The positive-sequence inductance of the reactor **110** with the neutral terminal is made large, so that most of positive-sequence of the arm currents Iu, Iv and Iw flowing through the respective arms **104***u*, **104***v* and **104***w* flow to the rotary electric machine **103**A. Thus, rotation driving can be efficiently performed.

However, the zero-sequence inductance of the reactor **110** with the neutral terminal must be made larger than a minimum value required for control of the DC current Idc.

Besides, when the zero-sequence inductance of the reactor **110** with the neutral terminal is decreased, magnetic flux generated in the reactor **110** with the neutral terminal by the DC current Idc can be decreased. Thus, there is an effect that the reactor **110** with the neutral terminal and the power conversion apparatus **102**A using the same can be miniaturized.

Next, an example of an inner structure of the reactor **110** with the neutral terminal will be described with reference to FIG. **6** and FIGS. **7**A and **7**B.

FIG. **6** shows a reactor **110**A with a neutral terminal as one structural example of the reactor **110** with the neutral terminal.

The reactor **110**A with the neutral terminal includes a U-phase core leg **1101**U, a V-phase core leg **1101**V and a W-phase core leg **1101**W.

A U-phase Zig winding **1102**U and a W-phase Zag winding **1103**W are wound around the U-phase core leg **1101**U. A V-phase Zig winding **1102**V and a U-phase Zag winding **1103**U are wound around the V-phase core leg **1101**V. Similarly, a W-phase Zig winding **1102**W and a V-phase Zag winding **1103**V are wound around the W-phase core leg **1101**W.

One end of the U-phase Zig winding **1102**U is connected to a point U, and the other end is connected to one end of the U-phase Zag winding **1103**U. The other end of the U-phase Zag winding **1103**U is connected to a point N. One end of the V-phase Zig winding **1102**V is connected to a point V, and the other end is connected to one end of the V-phase Zag winding **1103**V. The other end of the V-phase Zag winding **1103**V is connected to the point N. One end of the W-phase Zig winding **1102**W is connected to a point W, and the other end is connected to one end of the W-phase Zag winding **1103**W. The other end of the W-phase Zag winding **1103**W is connected to the point N.

In the U-phase core leg **1101**U, the U-phase Zig winding **1102**U and the W-phase Zag winding **1103**W are magnetically coupled so that magnetomotive forces due to zero-sequence current commonly flowing through the Zig winding **1102**U and the Zag winding **1103**W are cancelled.

In the V-phase core leg **1101**V, the V-phase Zig winding **1102**V and the U-phase Zag winding **1103**U are magnetically coupled so that magnetomotive forces due to zero-sequence current commonly flowing through the Zig winding **1102**V and the Zag winding **1103**U are cancelled.

Similarly, in the W-phase core leg **1101**W, the W-phase Zig winding **1102**W and the V-phase Zag winding **1103**V are magnetically coupled so that magnetomotive forces due to zero-sequence current commonly flowing through the Zig winding **1102**W and the Zag winding **1103**V are cancelled.

In other words, the respective Zig windings **1102**U, **1102**V and **1102**W and the respective Zag windings **1103**U, **1103**V and **1103**W of the reactor **110**A with the neutral terminal constitute zigzag connection. The zero-sequence currents (Idc/3) included in arm currents Iu, Iv and Iw flow through the reactor **110**A with the neutral terminal. Thus, the reactor **110**A with the neutral terminal cancels the magnetomotive forces due to the zero-sequence current (Idc/3), and DC magnetic fluxes generated in the respective core legs **1101**U, **1101**V and **1101**W can be made substantially zero. By this, there is obtained an effect that the reactor **110**A with the neutral terminal and the power conversion apparatus **102**A using the same can be miniaturized.

FIGS. **7**A and **7**B show a reactor **110**B with a neutral terminal as another structural example of the reactor **110** with the neutral terminal.

As shown in FIG. **7**A, the reactor **110**B with the neutral terminal includes a three-leg core **1104** including a U-phase core leg **1104**U, a V-phase core leg **1104**V and a W-phase core leg **1104**W.

A U-phase winding **1105**U is wound around the U-phase core leg **1104**U. One end of the U-phase winding **1105**U is connected to a point U, and the other end is connected to a neutral terminal N.

A V-phase winding **1105**V is wound around the V-phase core leg **1104**V. One end of the V-phase winding **1105**V is connected to a point V, and the other end is connected to the neutral terminal N.

Similarly, a W-phase winding **1105**W is wound around the W-phase core leg **1104**W. One end of the W-phase winding **1105**W is connected to a point W, and the other end is connected to the neutral terminal N.

As shown in FIG. **7**B, the U-phase core leg **1104**U, the V-phase core leg **1104**V and the W-phase core leg **1104**W constitute the three-leg core **1104**. That is, the reactor **110**B with the neutral terminal is the three-leg core reactor.

When the three-leg core **1104** is used, magnetic flux generated by magnetomotive force due to zero-sequence current (Idc/3) passes through a space outside the core having high magnetic resistance. Thus, the magnetic flux due to the zero-sequence current (Idc/3) can be reduced. Thus, there is an effect that the reactor **110**B with the neutral terminal and the power conversion apparatus **102**A using the same can be miniaturized.

Modified Examples

The invention is not limited to the above embodiments and includes various modified examples. For example, the above embodiments are described in detail in order to make the invention easy to understand, and the invention is not necessarily limited to one including all the described components. A part of components of one embodiment can be replaced by components of the other embodiment, and components of one embodiment can be added with components of the other embodiment. Besides, with respect to a part of components of the respective embodiments, addition/deletion/replacement of other components can be made.

A part or all of the respective components, functions, processing parts, processing units and the like may be realized by hardware such as an integrated circuit. The respective components, functions and the like can be realized by software in which a processor interprets and executes a program for realizing the respective functions. Information such as the program for realizing the respective functions, tables and files can be stored in a storage device such as a memory, a hard disk or a SSD (Solid State Drive), or a recording medium such as a flash memory card or a DVD (Digital Versatile Disk).

In the respective embodiments, control lines and information lines are shown which appear to be necessary for the description, and all control lines and information lines of a product are not necessarily shown. Actually, it may be regarded that almost all the components are mutually connected.

As modified examples of the invention, for example, the followings (a) to (d) are conceivable.

(a) The description of the power conversion apparatus **102**, **102**A holds true even when the direction of power is reversed. That is, in the power conversion apparatus **102**, **102**A, the rotary electric machine **103**, **103**A may be made a power generator, and the generated power may be supplied between the point P and the point N.

(b) In the power conversion apparatus **102**, **102**A, the rotary electric machine **103**, **103**A has three phases, and the number of the arms **104** is three. However, no limitation is made to this. In the power conversion apparatus, the rotary electric machine may have four or more phases, and the same number of arms **104** as the number of phases of the rotary electric machine may be used.

(c) As the structural examples of the reactor **110** with the neutral terminal of the second embodiment, the reactor **110**A with the neutral terminal (see FIG. **6**) constructed of the zigzag connection, and the reactor **110**B with the neutral terminal (see FIGS. **7**A and **7**B) including the three-leg core are described. However, no limitation is made to this. A different structured reactor with a neutral terminal capable of drawing a neutral terminal may be used in the power conversion apparatus.

(d) The energy storage element of the unit converter **105** is not limited to the electrolytic capacitor, and an electric double-layer capacitor, a secondary battery or the like may be used.

What is claimed is:

1. A power conversion apparatus comprising:

three or more arms in each of which one or more unit converters each including an energy storage element and capable of outputting an arbitrary voltage are connected in series;

a first node to which first ends of the respective arms is Y-connected, the first node being connected to a first side of a DC power supply, wherein

second ends of the respective arms are connected to first ends of respective Y-connected phase windings of a rotary electric machine, and

second ends of the Y-connected phase windings are connected to a second side of the DC power supply,

wherein each energy storage element is supplied with power through the first side or the second side of the DC power supply.

2. The power conversion apparatus according to claim **1**, further comprising a second node to which a neutral terminal of the rotary electric machine is connected.

3. The power conversion apparatus according to claim **2**, wherein the second node to which the neutral terminal of the rotary electric machine is connected is grounded.

4. The power conversion apparatus according to claim **1**, further comprising:

a reactor with a neutral terminal connected in parallel to the rotary electric machine; and

a second node to which the neutral terminal of the reactor with the neutral terminal is connected.

5. The power conversion apparatus according to claim **4**, wherein a positive-sequence inductance of the reactor with the neutral terminal is larger than a zero-sequence inductance.

6. The power conversion apparatus according to claim **4**, wherein the reactor with the neutral terminal has a zigzag connection.

7. The power conversion apparatus according to claim **4**, wherein a core of the reactor with the neutral terminal is a three-leg core.

8. The power conversion apparatus according to claim **4**, wherein the neutral terminal of the reactor with the neutral terminal is grounded.

9. The power conversion apparatus according to claim **1**, wherein a part or all of the unit converters are bi-directional chopper circuits.

10. The power conversion apparatus according to claim **1**, wherein a part or all of the unit converters are full-bridge circuits.

11. An electrical-mechanical energy conversion system comprising:

a power conversion apparatus which includes:

three or more arms in each of which one or more unit converters each including an energy storage element and capable of outputting an arbitrary voltage are connected in series,

a first node to which first ends of the respective arms is Y-connected, the first node being connected to a first side of a DC power supply, wherein

second ends of the respective arms are connected to first ends of respective Y-connected phase windings of a rotary electric machine, and

second ends of the Y-connected phase windings are connected to a second side of the DC power supply,

wherein each energy storage element is supplied with power through the first side or the second side of the DC power supply; and

a rotary electric machine to which a mechanical load is connected and in which another end of the respective arms is connected to one end of respective phase windings.

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